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Integrity detection of mooring chains by the approach of thermography

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ABSTRACT: Reliability and safety issues of mooring chains are causing concern in recent years. Accordingly, some efforts have been made for detecting the structural integrity of mooring chains. However, a fully successful mooring chain condition monitoring technique has not been achieved today. This is largely due to the fact that mooring chains are submerged in water and the currently available non-destructive testing technologies are difficult to apply in wet environment. To overcome this issue, a new mooring chain condition monitoring method is studied in this paper with the aid of thermography technique. The research is conducted based on two philosophies, i.e. (1) the mooring chain material has much higher thermal conductivity than that of water. Therefore, when the mooring chain is heated, the thermal energy will transmit mostly inside the chain, rather than dispersing in water; (2) the defects occurring in the mooring chain will disturb the transmission of thermal flow inside the mooring chain and consequently change the distribution of the temperature in the adjacent area. To demonstrate the effectiveness of the proposed method, both numerical and experimental researches are conducted in this paper. The research results have shown that thermography is indeed valid in detecting the integrity of mooring chains.

1 INTRODUCTION

There are a variety of non-destructive testing techniques that have been developed for addressing various structural integrity testing and assessment issues in different fields, such as those depicted in References (see Blitz 2012, Sanjeev et al. 2013, Amenabar 2011 and Garcia-Martin et al. 2011). However, few of them is applicable to monitoring the structural integrity of mooring chains as the mooring chains are full submerged in the water located in harsh marine and offshore environment.

In order to tackle this issue, much effort has been made by the scholars and industrialists in recent years, although a cost and technically effective mooring chain condition monitoring technique has not been successfully achieved till today. This is because so far, almost all the existing mooring chain condition monitoring techniques and systems (see AVT Reliability 2017, Seatools 2017, Lugsdin 2017), with the exception of the ultrasonic guided wave technique developed by TWI (see TWI 2013), are originally designed for detecting a broken mooring line rather than detecting and monitoring the growth of the defects occurring in it. In reality, a defective mooring chain may but is not necessary lead to broken of the mooring line when it is subject to extreme loads. For example, Remotely Operated Vehicle (ROV) inspection has been popularly adopted for inspecting typical damage and loss of integrity of marine structures. It can be equally applied to the inspection of mooring chains. However, ROV inspection only provides snapshot of the surface of mooring chains, which could be covered by thick layer of marine lives. Therefore, visual inspection via ROV is unable to provide the operator with reliable information about the actual structural health condition of mooring chains. Moreover, the application of ROV inspection is limited by weather windows and access, it is unlikely to realize the continuous monitoring of the mooring chain. In order to obtain continuous monitoring data from mooring chains, AVT Reliability attempted to use strain gauge to monitor the integrity of mooring chains and applied the devised strain gauge based measurement system to assessing the integrity of the 9 mooring chains installed on a 870,000 barrel oil storage tanker (AVT Reliability 2017). The novelty of such a system is that it does not directly measure the chain tensions but instead, monitors the stresses in the buoy structural steelwork in reacting those same chain tensions. This has the advantage that the instrumentation can be mounted internally inside the buoy in a clean dry environment. However, the measured stresses from the buoy structural steelwork are not only dependent on the integrity of mooring chains, but also affected by the motions of the storage tanker and the external loads acting on it. Therefore, the AVT system is effective in detecting a broken mooring line, however ineffective in detecting and monitoring the incipient defects occurring in it. Apart from AVT Reliability, the other companies also develop mooring chain integrity monitoring systems using different techniques. For example, Seatools developed the mooring chain inclination measurement technique (Seatools 2017), Tritech International Ltd developed a multi-beam sonar technique (Lugsdin 2017), and so on. But they all for detecting whether the mooring lines are well connected to the floating structures, rather than for detecting the defects occurring in the chains. To tackle this issue, TWI developed an automated ultrasonic guided wave technique for monitoring mooring chains (TWI 2013). Laboratory test has shown that such a technique does work in improving the accuracy, consistency and repeatability of inspection results. But it requests to make minimal surface preparation before conducting inspection. However, this is very difficult to implement in the practical application. Additionally, the high cost of the associated robotic delivery system also limits the extensive application of such an ultrasonic guided wave technique. In view of this, a new mooring chain condition monitoring technique is studied in this paper with the aid of thermography technique. The details of the numerical and experimental research are given below.

2 HYPOTHESES

According to the fundamental theory of thermodynamics, the rate of heat flow can be described as (Borgnakke et al. 2003):

$$\frac{Q}{t} = \frac{\kappa A}{d} \Delta T \tag{1}$$

where Q = the amount of heat transferred in a time t; κ = the thermal conductivity constant for the material; A = the cross sectional area of the material transferring heat; d = the thickness of the material; and ΔT = the difference in temperature between one side of the material and the other.

From (1), there are two hypotheses can be inferred that: (1) since the thermal conductivity κ for steel is 46 Watts/meter−°C, which is much higher than the thermal conductivity of water (i.e. κ for water is only 0.58 Watts/meter−°C), the heat flow will be transferred much faster in steel than in water. Accordingly, when the steel mooring chain is heated from one end, the majority of heat flow will be transferred inside the steelwork of the chain rather than being dissipated in the water around it; (2) equation (1) shows that the cross sectional area A is inversely proportional to the temperature difference ΔT. That means when the same amount of heat is transferred inside the chain, the defect resulted change in the cross sectional area A will be indicated by the change in temperature or temperature distribution. In the meantime, the heat flow will be transferred automatically along the path which has smaller thermal resistance.

If the above two hypotheses are true, the integrity of the mooring chain then can be detected via observing the distribution of mooring chain temperature. In other words, the discontinuity in temperature distribution may indicate the presence of defect in the structure of mooring chain.

3 NUMERICAL RESEARCH

In order to demonstrate the aforementioned two hypotheses and investigate the transferring process of the heat flow insider a mooring chain when it is heated, the numerical model of mooring chains is developed in ANSYS 15. In each chain, the center to center distance is 24 mm, the width is 18 mm. The radius of the side circle is 4 mm. Then, different types of defects were artificially made on the model through changing its geometries. The mooring chains with different sizes of cracks with 0.5 mm clearance are shown in Figure 1.

In ANSYS 15, the steady state thermal analysis are conducted. In the engineering data section of the analysis, steel was chosen as the material for the mooring chain. In the calculation, the mooring chains are meshed and moreover, mesh refinement properties were used for building finer meshes particularly in the vicinity areas of the defects, such as the example given in Figure 2.

In the numerical calculations, both environmental temperature 22 Celsius and heating temperature

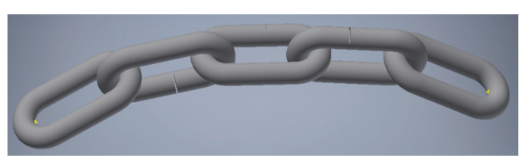


Figure 1. The mooring chains with different integrity conditions.

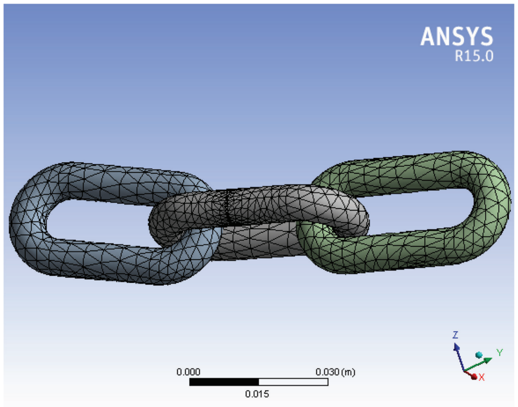


Figure 2. Mesh and mesh refinement of the mooring chains.

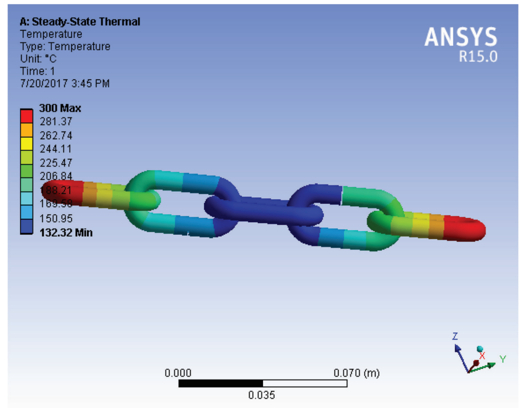


Figure 4. Numerical result obtained when a fully cracked mooring chain is heated from both ends.

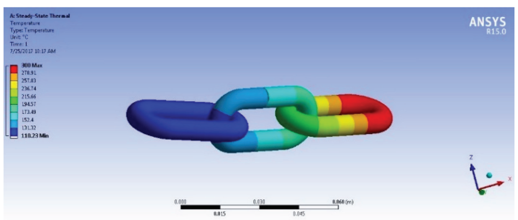


Figure 3. Numerical result obtained when a partially cracked mooring chain is heated from one end.

300 Celsius are specified in the steady state thermal column. The convection film coefficient is also defined in this section. The value is taken as 22 W/m^2°C. When the heating temperature is applied at one end of the mooring chains while the other end is fixed and no temperature is applied, the numerical calculation results for a partially cracked mooring chain are graphically shown in Figure 3.

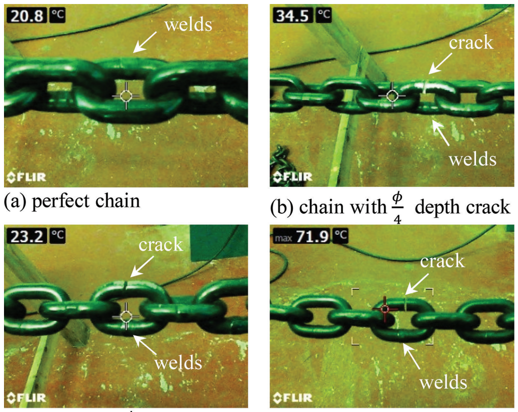
From Figure 3, it is found that: (1) the discontinuity of the temperature observed from the upper part of the defective mooring chain proves that the defect in the mooring chain does disturb the transfer of heat flow, thus may cause visible temperature difference in the vicinity area of the defect; (2) the asymmetric distribution of the temperatures of the upper and lower parts of the defective mooring chain proves that heat flow is more easily to be transferred along the path that has smaller thermal resistance; (3) although in the numerical simulation, the mooring chain is assumed to be placed in air rather in water, the visible temperature differences prove that when the steel mooring chain is heated from one end, the majority of heat flow will be transferred inside the steelwork of the chain rather than being dissipated outside the chain as the thermal conductivities of air and water are similar and much smaller than that of steel mooring chain; and (4) moreover, the profile of the temperature distribution around the defect indicates the size of the defect. In order to further verify the findings from Figure 3, a fully cracked mooring chain is heated from both ends, as shown in Figure 4.

From Figure 4, it is clearly seen that the aforementioned four findings are also valid when the mooring chain is completely cracked and heated from both ends. This indicates that, in the sense of theory, the thermography do have potential to be applied to detect and monitor the defects occurring in mooring chains.

4 EXPERIMENTAL RESEARCH

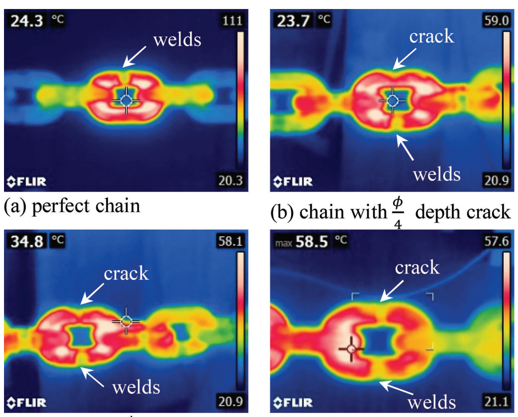
In order to physically demonstrate the interesting findings observed in numerical research, experimental research is organized in laboratory. The perfect and defective chains with different sizes of cracks are shown in Figure 5. Where, the chain cracks are artificially made using hacksaw.

In the experiment, the influences of the cracks on the chain temperature distributions in their vicinity areas are investigated in two scenarios in order to find a better heating method that can lead to more reliable condition monitoring result. In the first scenario, the mooring chain being investigated is heated from the both ends of it; while in the second scenario the mooring chain is headed from only one end. The experimental results obtained in the first scenario are shown in Figure 6.



(a) perfect chain
(b) chain with $\frac{\phi}{4}$ depth crack
(c) chain with $\frac{\phi}{2}$ depth crack
(d) chain with through crack

Figure 5. Mooring chains used in the experiments.



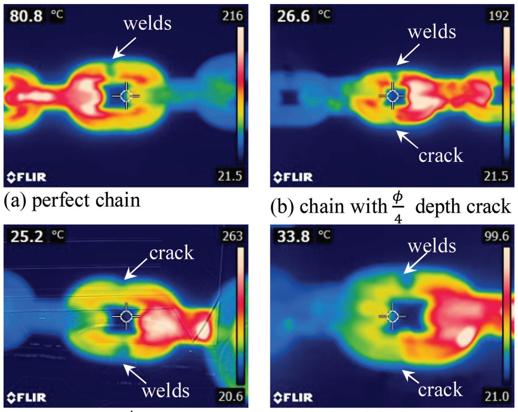
(a) perfect chain
(b) chain with $\frac{\phi}{4}$ depth crack
(c) chain with $\frac{\phi}{2}$ depth crack
(d) chain with through crack

Figure 6. Experimental results obtained when the chains are heated from both ends.

From Figure 6, it is found that when the mooring chain is perfect and has no any defect inside the chain structure, the temperature is distributed evenly and smoothly over the chain except at welds, where the temperature is obviously smaller than in others due to the much higher thermal conductivity of the welding material. But when a crack is present in the chain, the even distribution of the temperature over the chain will be discontinued. Consequently, a concave profile can be observed from the cracking area in the thermal image. Moreover, it is found that the larger the size of the crack, the deeper the concave profile tends to be. This is because the air or water in the clearance of the crack has lower thermal conductivity than that of the mooring chain material. Therefore, the air or water temperature in the crack clearance is lower than that of the steelwork of the chain. From such an observation, it can be inferred that a partial through crack can partially stop the transfer of heat flow, although the heat flow is still able to be transferred through the un-cracked section. But when the crack continues to propagate and finally becomes a full through crack in the end, the transfer of heat flow will be significantly limited by the crack. In this worst case, the heat flow in the cracking area is transferred only via the air or water in the clearance of the full through crack. In general, from these experimental results obtained in the first scenario, it can be concluded that the crack occurring in the mooring chain can be readily detected using thermographic technique. Moreover, the size of the crack can be approximately understood through observing the concave depth of the temperature profile in the vicinity area of the crack. However, more accurate evaluation of the crack is difficult to achieve due to the limitation of observation.

In order to further improve the accuracy of the crack evaluation, the experiment is repeated in the second scenario. But the difference from the first scenario is the mooring chains being investigated are heated from only one end. The corresponding experimental results are shown in Figure 7.

From Figure 7, it is found that the similar phenomena observed from the first scenario (see Figure 6) also can be observed. But the assessment of the crack is not easy to achieve through observing the concave depth of the temperature profile because the concave feature caused by the crack cannot be clearly observed in the second scenario. Accordingly, a quantitative assessment method is developed in the following by using the temperature reading function of the thermographic camera. In addition, it is noticed that there is a temperature value displayed at the top left of the picture, such as $80.8°C$ in Figure 7a, $26.6°C$ in Figure 7b, $25.2°C$ in Figure 7c, and $33.8°C$ in Figure 7d. These values indicate the temperatures at the positions located by the circle with a cross. With the aid of this special temperature reading function provided by the thermal camera, the temperature at any position in the thermal image can be readily obtained. Then, the temperatures at two specific positions are measured for developing the quantitative assessment criterion. One is the temperature T_h measured at the heating source position, another is the temperature T_c measured at the other side of the crack. Since the temperature at the heating source position is the highest temperature in the thermal image, the value of T_h is usually the maximum value shown in the grey scale of the image, i.e. $T_h = 216\,^oC$ for Figure 7a, $192\,^oC$ for Figure 7b, $263\,^oC$ for Figure 7c, and $99.6\,^oC$ for



(a) perfect chain (b) chain with $\frac{\phi}{4}$ depth crack

(c) chain with $\frac{\phi}{2}$ depth crack (d) chain with through crack

Figure 7. Experimental results obtained when the chains are heated from one end.

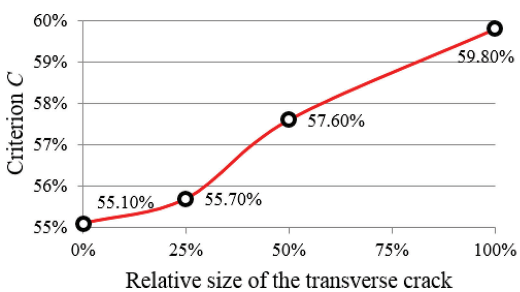


Figure 8. Quantitative assessment of the crack occurring in the mooring chain.

Figure 7d. Therefore, in fact T_c is the only value that needs to be measured by moving the circle with a cross to the other side of the crack. Once the value of T_c is obtained, the following quantitative assessment criterion can be calculated, i.e.

$$C = \frac{T_h - T_c}{T_h} \times 100\% \tag{2}$$

In essence, the criterion C measures the significance that the crack disturbs the heat transfer along the mooring chain. When the crack increases in size, the local heat transfer ability of the chain will decrease due to the reduced contact area of the metal. This will lead to a small value of T_c and consequently a large value of criterion C when the heating temperature T_h is constant. Therefore, the criterion C can be used to quantitatively assess the size of a transverse crack occurring in the mooring chain. In the experiment, the values of T_c have been read from the images shown in Figure 7. They are $T_c = 97\,^oC$ for Figure 7a, $85\,^oC$ for Figure 7b, $111.5\,^oC$ for Figure 7c, and $40\,^oC$ for Figure 7d. Substitute the values of T_h and T_c into (2), the criterion C is calculated and the results are shown in Figure 8.

From Figure 8, it is clearly seen that as expected, the value of criterion C does increase gradually with the increasing depth of the crack. This means that the larger the size of the crack, the more significant the influence of the crack tends to be in the heat transfer process. This fully demonstrates that the proposed quantitative evaluation method does work in assessing the crack occurring in the mooring chain.

5 CONCLUSIONS

In order to explore a feasible method for monitoring the health condition of mooring chains, both numerical and experimental researches are conducted in the paper to investigate the potential of thermography technique in detecting transverse cracks occurring in mooring chains. From the work reported above, the following conclusions can be drawn:

1. When the mooring chain is perfect in structural integrity, the temperature is smoothly distributed over the chain except at welds, where the temperature is smaller than in other chain parts due to the higher thermal conductivity of welding materials in comparison of that of the steel material of mooring chain;
2. When the mooring chain is heated from its both ends, a clear concave will appear in the temperature profile in the presence of a transverse crack in the mooring chain. Moreover, the larger the size of the crack, the deeper the concave tends to be. Therefore, the concave in the temperature profile is a good indicator of the crack and its propagation when the mooring chain is heated from the both ends of it;
3. In comparison of the scenario that the mooring chain is heated from the both ends of it, more accurate assessment of the crack can be achieved when the mooring chain is heated from only one end. Experiment has shown that the proposed quantitative evaluation method can successfully predict the presence and growth of the crack when the chain is heated from only one end;
4. The aforementioned numerical and experimental researches have demonstrated that thermography technique does have potential to be applied to condition monitoring mooring chains. However, further research is still required to develop an appropriate method to heat the mooring chain in a completely wet environment.

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REFERENCES

Amenabar I., Mendikute, A., Lopez-Arraiza, A., Lizaranzu, M. & Aurrekoetxea, J. 2011. Comparison and analysis of non-destructive testing techniques suitable for delamination inspection in wind turbine blades, *Composites Part B: Engineering* 42(5): 1298–1305.

AVT Reliability, https://www.avtreliability.com/media-centre/case-studies/mooring-line-integrity-monitoring, latest access on 20/10/2017.

Blitz, J. 2012. *Electrical and magnetic methods of non-destructive testing*, Springer.

Borgnakke, C. & Sonntag, R.E. 2003. *Fundamentals of thermodynamics*, John Willey & Sons Inc.

Garcia-Martin, J., Gomez-Gil, J. & Vazquez-Sanchez, E. 2011. Non-destructive techniques based on eddy current testing, *Sensors* 11(3): 2525–2565.

Lugsdin, A., Real-time monitoring of FPSO mooring lines, risers. http://www.tritech.co.uk/uploadedfiles/RAMSSeaTech%20editorial.pdf, latest access on 20/10/2017.

Sanjeev, K.V., Sudhir, S.B. & Saleem A. 2013. Review of non-destructive testing methods for condition monitoring of concrete structures, *Journal of Construction Engineering* 2013:1–11.

Seatools, http://www.seatools.com/news/completion-mooring-monitoring-project/?gclid=CI2wpNnVuNYCFYqU7QodQpUEFQ, latest access on 20/10/2017.

TWI, An effective methodology for implementing structural health monitoring and in-service inspection of mooring chains, 2013.